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BRAYTON CYCLE NUCLEAR SPACE POWER SYSTEMS
AND THEIR HEAT-TRANSFER COMPONENTS

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ABSTRACT

Electric power requirements for space missions will continually increase as our nation's space program progresses. The most promising power-generation technique for near future application to missions requiring power levels greater than several kilowatts for 1 year or longer is the indirect conversion closed-loop heat engine. One of the thermodynamic systems that merits consideration for such applications is the Brayton cycle, which uses an inert gas as the thermodynamic working fluid. The heat-transfer components constitute an important part of any Brayton cycle, and it is the purpose of this paper to discuss these components.

Several configurations being considered for Brayton cycle space power systems are described and the required heat-transfer components are indicated. Important system characteristics such as cycle efficiency and radiator area are related to such heat-transfer-component parameters as reactor temperature, component-pressure drops, heat-exchanger effectiveness, and radiator-heat-transfer coefficient. The heat-transfer-component features necessary to make a Brayton cycle attractive for space use are emphasized, and the ability of available heat-transfer components to achieve the required performance and reliability is discussed.

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INTRODUCTION

Electric power requirements for space missions will continually increase as our nation's space program progresses. The most promising power-generation technique for near future application to missions requiring power levels greater than several kilowatts for 1 year or longer is the indirect-conversion closed-loop heat engine. Such a system utilizes the conversion of nuclear or solar heat to mechanical energy by means of a turbine located in a working fluid loop. The two thermodynamic cycles most often considered for such an application are the Rankine cycle, utilizing a boiling and condensing-metal working fluid, and the Brayton cycle, utilizing an inert-gas working fluid.

Brayton cycles, which have performed most satisfactorily in turbo-prop and turbojet engines, have not been as seriously considered for space power systems as Rankine cycles have been, because the ability of the Rankine cycle to reject heat at a constant temperature results in radiator areas and weights smaller than those for a Brayton cycle. For applications, however, such as extraterrestrial based generating stations, auxiliary power for space stations, and advanced communications satellites, low powerplant weight, although always desirable, is not

absolutely necessary. The Brayton cycle merits consideration for these applications because its use eliminates (1) the problems connected with two-phase flow (boiling and condensing) in a zero gravity environment, (2) the presence of a severely corrosive working fluid, and (3) the possibility of erosion damage in the rotating components. Much of the basic technology for the Brayton cycle is presently available, and this system has a good potential for multiple starts as well as for achieving the required long time reliability.

In view of the above considerations, an investigation of the Brayton cycle for space power systems was undertaken. Studies were made of the thermodynamic characteristics of such systems as well as of the heat-transfer components and the turbomachinery components. Glassman and Stewart (ref. 1) reported the results of the cycle thermodynamics study. It is the purpose of this paper to describe the heat-transfer components and indicate how the various component parameters affect system performance.

SYSTEM CONFIGURATIONS

Several configurations have been considered for Brayton cycle space power systems. The simplest of these, the one-loop system, is shown schematically in figure 1(a) and thermodynamically in figure 1(b). The gaseous working fluid is heated to its maximum temperature in the reactor and then expanded through the turbine, where the mechanical power required to drive the compressor and alternator is produced. In the recuperator, the turbine exit gas is cooled as it transfers heat to the compressor exit gas. Final cooling of the gas to the minimum cycle temperature takes place in the radiator, where the excess heat is rejected to

space. The gas is then compressed, heated in the recuperator, and returned to the reactor. Thermodynamic analyses (e.g., ref. 1) have shown the cycle temperature interrelationships which are necessary for system optimization. The ratio of turbine exit temperature to turbine inlet temperature must be about 0.70 to 0.80 and the ratio of radiator exit temperature to turbine inlet temperature must be about 0.25 to 0.35.

If a liquid-metal-cooled reactor is to be used as the cycle heat source, a heating loop with a liquid-to-gas heat exchanger must be added to the system, as shown in figure 2. The liquid-metal heat-transfer fluid circulates continuously between the reactor and the heat exchanger, which now serves as the heat source for the gas loop. This two-loop system has the advantages of better isolation of fission products and separation of reactor and power system development problems; however, system complexity has increased. Reactor availability would probably be a major factor if a choice had to be made between a one- or two-loop scheme.

A liquid radiator, for reasons to be discussed later, offers a potential weight savings over a gas radiator. If a liquid radiator is found to be preferable to a gas radiator, a cooling loop with a gas-to-liquid heat exchanger must be added to the system. Figure 3 shows a three-loop system including both heating and cooling loops. The liquid coolant, which can be metal, organic, or aqueous depending on the temperature level, circulates continuously between the heat exchanger, which now serves as a heat sink for the gas, and the radiator. A liquid cooling loop offers the possible advantage of added mission reliability due to the ease of segmentation (i.e., use of several loops in parallel to supply the required cooling); however, this advantage may be offset by an

Increase in system complexity.

As seen from the foregoing system descriptions, heat-transfer components constitute an important part of any Brayton cycle system. The heat-transfer components can be classified into three groups: reactors, heat exchangers, and radiators. Both gas-cooled and liquid-metal-cooled reactors are considered as potential heat sources. The heat exchangers include the gas-to-gas recuperator, liquid-to-gas heater, and gas-to-liquid cooler. Both gas and liquid radiators are considered as potential heat-rejection components.

SYSTEM AND COMPONENT CHARACTERISTICS

System performance and size depend to a large extent on the performance of the heat-transfer components. Important system characteristics such as cycle efficiency and radiator size are functions of such heat-transfer-component characteristics as reactor-coolant exit temperature, component pressure drops, heat-exchanger effectiveness, and radiator fluid heat-transfer coefficient. Since the radiator may be extremely large, radiator size is an important consideration in any system design. For the purpose of showing how the above mentioned component characteristics affect the radiator, prime radiator area will be used to represent radiator size. Prime radiator area is here defined as the radiating area required for either a radiator without fins or one with 100 percent efficient (no resistance to heat conduction) fins. Actual finned tube panel area, however, will be used when discussing radiator-design philosophy.

It is the purpose of this section to (1) describe, in a general manner, the various heat-transfer components, (2) show how system performance is affected by heat-transfer component parameters, and (3) discuss

the ability of currently available heat-transfer components to achieve the desirable performance levels.

Reactors

Both gas-cooled and liquid-metal-cooled reactors have been considered as potential system heat sources. The requirements for a reactor for use in a space power system are somewhat unique. Reactor physical size should be small in order to minimize shield size and weight. It is also desirable to minimize reactor weight, but this is not as critical as minimizing the physical dimensions. Reactor-power requirements (on the order of several hundred kilowatts) for space auxiliary power systems are modest when compared to the hundreds of megawatts which may be encountered in existing reactor technology. The requirement for a 10,000 hour operating life may be a problem area since, at present, no data are available that can even be extrapolated with any certainty to this operating time.

Reactor temperature. - A major consideration in the selection of a reactor to serve as the cycle heat source is the maximum fluid temperature which can be obtained from that reactor. For the case of a gas-cooled reactor system, this temperature will be the turbine inlet temperature for a liquid-metal-cooled reactor system, the turbine inlet temperature must be somewhat less than the reactor exit temperature because of the intermediate liquid-to-gas heat-transfer step. The effect of turbine inlet temperature on prime radiator area for several sink temperatures is shown in figure 4 for a typical set of system design parameters. At a turbine inlet temperature of 1700° R and a sink temperature of 400° R, the required prime radiator area is about 61.5 square feet

per kilowatt of shaft power to the alternator. It can readily be seen that Brayton cycles operating at this temperature and producing more than 30 kilowatts of shaft power would require thousands of square feet of radiator area. For the 400° R sink temperature, an increase in turbine inlet temperature from 1700° to 2500° R results in a fourfold decrease in radiator area. Considering the large radiator size required for a turbine inlet temperature of 1700° R, an increase in turbine inlet temperature above this level is extremely advantageous to the system. For the range of turbine inlet temperatures shown in Figure 4, the effect of sink temperature on radiator area is small for sink temperatures up to about 400° R but becomes quite significant, especially at the lower turbine inlet temperature levels, as sink temperature increases beyond 400° R. Desirable turbine inlet temperatures, in excess of 2000° R, are higher than present reactor technology will allow, but are modest when compared to the desirability of temperatures in excess of 4000° R for nuclear rockets.

Reactor types. - Several types of reactor systems have been developed, but not all are applicable to space power systems. The reactor property known as criticality results in some reactor configurations that are extremely large and, therefore, not usable. Other reactors are of the desired small size, but cannot produce the required temperature. Three types of reactors, each of which can be either gas- or liquid-cooled, will be discussed to illustrate these points.

The concept that appears most promising in theory is the fast spectrum reactor. This reactor is of minimum size, although possibly not of minimum weight. It is called fast because the fission process is caused

by neutrons of fast velocity or high energy. Fission by fast neutrons is a low probability process requiring a high fuel inventory to achieve a critical system. Considering its present state of development, the successful design, construction, and operation of a high-temperature fast reactor is probably 5 years or more in the future, and there are probably many problem areas which have not yet been discovered. One example of a fast reactor under development for space power systems is the liquid-metal-cooled SNAP-50 reactor, which is being designed for a thermal rating of 8 to 10 megawatts and an operating life of 10,000 hours. The reactor coolant is lithium, which may leave the reactor at about 2000° F.

Most reactor experience is concentrated in the thermal class of reactors. The fission process in this type of reactor is the result of thermal, or slow velocity, neutrons. This is a comparatively high probability process and results in modest fuel requirements for criticality. Thermal reactors may be either of the homogeneous or heterogeneous type, depending upon whether the fuel and moderator are intimately mixed or placed in separate regions. A major problem is to find a moderator material that is very efficient at slowing down the neutrons, which are born fast, to the desired slow velocity without losing them in some manner. The most suitable material for this purpose has been found to be hydrogen; hydrogen-bearing materials, however, are not stable at the desired high temperatures.

One example of a hydrogen-moderated homogeneous thermal reactor being developed for space power systems is the SNAP-8 reactor, which is being designed for a dual capability of 300 and 600 kilowatts thermal operation for 10,000 hours. The reactor coolant is the eutectic sodium-

potassium alloy (NaK-78), which leaves the reactor at 1760° R, a temperature that is near the upper limit for hydrogen-moderated homogeneous thermal reactors but is near or below the lower limit of desirability for Brayton cycle space power systems. Higher temperatures can be obtained from homogeneous reactors by using moderating materials that are less efficient than hydrogen, but that would withstand the desired high temperatures. Two materials, graphite and beryllium oxide, are usable and reactors using these materials have been developed. Although these reactors have somewhat limited operating experience, they have achieved the maximum fluid outlet temperatures for operating reactors to date. Reactors of this type, however, are extremely large in size for criticality reasons.

In a heterogeneous thermal reactor it is possible to have the fuel elements at a higher temperature than the moderator, and thereby, be able to obtain the desired high temperature while using some of the better moderator materials. The best high-temperature gas-cooled reactor operating experience has been obtained with this type of reactor as part of the Heat-Transfer Reactor Experiment (HTRE) of the Aircraft Nuclear Propulsion (ANP) program (ref. 2). Considerable success was achieved in operating a reactor, with a gas outlet temperature approaching 2000° R, up to the total integrated power output (product of power and time) required for an auxiliary space power system. The HTRE-3 reactor operated at a power level of about 30 megawatts for 126 hours.

The HTRE reactor is unsatisfactory for space power systems because of its large size, which is dictated by the heat-transfer requirements of the much larger thermal output as well as the criticality requirement.

While the size requirement dictated by criticality must always be met, a reduction in reactor size is possible through the reduced power requirement. The feasibility of a smaller reactor to produce the same gas outlet temperature at lower power levels depends on the development of a reactor with less void volume. This is a design problem requiring, at most, a modest extension of existing technology. Such a size reduction, however, has limitations unless the fuel-element temperature can be raised. The HTRE program stopped with the use of a nichrome-type fuel element. A refractory-metal fuel element appears to be a reasonable next step.

On the basis that most of the problems are known, although not necessarily solved, for the heterogeneous thermal system it appears that a gas-cooled reactor of this type could be built more quickly than any other. Although this may not represent the ultimate in reactor design, it does appear to be a feasible design that could be built in a few years if a development effort were made. The basic feasibility of this type of reactor for a Brayton cycle power system has been demonstrated by the ML-1 powerplant (ref. 3) which is a land-based Brayton system designed to produce 300 to 500 kilowatts of electricity. The water-moderated ML-1 reactor was designed for a nitrogen exit temperature of 1660° R, a temperature somewhat lower than desired for a space power system.

Heat Exchangers

Effectiveness. - The effectivenesses of the various heat exchangers have an important effect on system performance. The gas heater and gas cooler effectiveness primarily affect radiator area through a change in radiator temperature. As the effectiveness of the gas heater increases,

turbine inlet temperature approaches reactor exit temperature and the radiator temperature level increases accordingly. As the effectiveness of the gas cooler increases, the temperature of the liquid coolant increases, thereby again increasing radiator temperature level. These increases in radiator temperature result in a reduction in radiator area.

The effectiveness of the recuperator affects both cycle efficiency and radiator area. Figure 5(a) shows cycle efficiency as a function of recuperator effectiveness for a typical set of system design parameters. As seen from this figure, cycle efficiency increases with recuperator effectiveness, and the use of a recuperator operating with an effectiveness of 0.86 results in a cycle efficiency double that obtainable without a recuperator. Cycle efficiency is the ratio of work output to heat supplied from the reactor; consequently, the increase in cycle efficiency with increasing effectiveness occurs because, as more heat is supplied to the gas in the recuperator, less heat must be supplied by the reactor.

A twofold increase in cycle efficiency through the use of a recuperator results in a 50 percent reduction in the heat required from the reactor and a reduction of more than 50 percent in the heat to be rejected by the radiator. The effect of this decrease in heat rejected on radiator area is shown in figure 5(b) where prime radiator area is plotted against recuperator effectiveness for a typical system. For an effectiveness of 0.86, the value that resulted in a twofold increase in cycle efficiency, the required radiator area is about 80 percent of that required without a recuperator. Although radiator heat load, as mentioned above, has been more than halved, the reduction in radiator area is not proportionately as much because the area is being removed from the hot (most efficient)

end of the radiator. However, considering the large size of the radiator, such an area reduction is still quite significant. Another advantage of high recuperator effectiveness is a decrease in turbomachinery pressure ratio (ref. 1).

Pressure drop. - The selection of heat-exchanger effectiveness for a system design must be made by balancing the above mentioned advantages against the disadvantages of increasing heat-exchanger weight and pressure drop with increasing effectiveness. The heat-exchanger pressure drops, as well as the pressure drops in the gas-cooled reactor and gas radiator, significantly affect system performance, as can be seen from figures 6(a) and (b), where cycle efficiency and prime radiator area, respectively, are plotted against the sum of the individual component percentage pressure drops for a typical system having a gas radiator and a fixed turbine inlet temperature. Each component pressure drop is expressed as a percentage of the inlet pressure to that component, and the individual percentages are summed to obtain the abscissa in figure 6. The pressure drops are expressed in this manner because this is the way they enter into the cycle thermodynamic equations (ref. 1). Figure 6(a) shows the manner in which the component pressure drops affect cycle efficiency. As the sum of the component pressure drops increases from 0 to 35 percent, cycle efficiency is approximately halved. The effect of such a pressure-drop increase on prime radiator area is seen from figure 6(b); radiator area increases more than threefold as the sum of the component pressure drops increases from 0 to 35 percent. Consequently, high percentage pressure drops must be avoided in the design of the heat-transfer components. The selection of a design pressure drop for a heat-transfer component must be based on a trade-off analysis,

since an increase in pressure drop will, on one hand, tend to reduce the size of that component through an increase in heat-transfer coefficient but, on the other hand, tend to increase the size of all components through a decrease in cycle efficiency.

Exchanger types. - Good system performance, as indicated above, depends to a large extent upon the obtainment of low weight heat exchangers which operate with high effectiveness and low pressure drop. The choice of configuration for the Brayton cycle heat exchangers appears to be the compact extended surface units such as the finned tube and plate-fin types. Rotating matrix configurations have the potential for reducing recuperator weight; however, the problem of leakage and carryover losses, which can be quite detrimental to system performance, must be studied before a rotating configuration can be considered. The inherent simplicity and reliability of the stationary surface configurations, as well as the availability of design data, resulted in the choice of these configurations for this study.

There are many compact heat-exchanger surfaces, as well as the heat-transfer and flow-friction data for these surfaces, presented in the published literature. In addition, there are also many proprietary designs for efficient and compact heat-exchanger surfaces. The most extensive study, known to the authors, of compact heat-transfer surfaces was the work sponsored by the Office of Naval Research and performed at Stanford University during the past 15 years. Among the surfaces studied were finned-tube surfaces with both circular and flat tubes and plate-fin surfaces with a variety of fin types such as plain, louvered, strip, wavy, pin, offset rectangular, and triangular. The results of the first

several years of this study were presented by Kays and London in reference 4 and included data for more than 20 finned-tube surfaces and 30 plate-fin surfaces. Later results are presented in references 5 to 8. It is interesting to note that five of the eleven surfaces presented in reference 8 had area densities in the range of 600 to 1330 square feet per cubic foot, while of the 33 plate-fin surfaces described in reference 4, only two had area densities as high as 500 square feet per cubic foot. This comparison provides some measure of the state-of-the-art advance since 1954 in fabricating highly compact surfaces. The surface in reference 6 that had an area density of 1330 was of stainless-steel construction and, therefore, well suited to high temperature service.

Both the basic heat-transfer and flow-friction design data and the fabrication techniques are in existence for a large number of surface configurations. The extension of this technology for application to high-temperature heat exchangers, however, will require some development effort.

Radiator

The radiator for a Brayton cycle space power system, as indicated previously, will require from hundreds to thousands of square feet of radiating area, depending on system power level and turbine inlet temperature. Since the radiator must operate in outer space, where high-speed meteoroids are present, the fluid passages have to be protected against puncture by these meteoroids. Meteoroid protection is generally provided by a layer of armor around the fluid passages. The required armor thickness depends on such factors as meteoroid population density, meteoroid properties, radiator material properties, radiator size, mission time,

and desired protection probability. Unfortunately, there is still much uncertainty concerning the values of some of these factors and the exact manner in which they influence required armor thickness. It has been estimated (ref. 9) that more than 50 percent of the radiator weight may be in the form of meteoroid protection. The requirement for meteoroid protection armor can result in the radiator being extremely heavy and possibly accounting for more than half of the total system weight. Such a large and heavy radiator has never been built for operation in space. Before the design and fabrication of a large space radiator is attempted, consideration must be given to methods for reducing its size and/or weight.

It is the purpose of this section to review certain of these preliminary considerations as they apply to Brayton cycle radiators. Such factors as external fin and tube configurations, tube size, armor material, internal fins, and a liquid cooling loop, can significantly affect radiator size and/or weight.

Geometry. - Radiator geometry has an important effect on radiator size and weight. Finned-tube radiators, although requiring larger areas than unfinned radiators, offer considerable weight savings over the unfinned radiators. This weight savings results primarily from the fact that only the tubes have to be armor-protected against meteoroid puncture; the fins, consequently, can be reasonably thin. Several finned-tube geometries are presented in figure 7. The central-fin geometry with simple armor protection is shown in figure 7(a). Figure 7(b) shows the central fin with bumper. The open-sandwich geometry (fig. 7(c)) appears attractive for cylindrical or conical radiators. The fin for radiating

heat also functions as a bumper in the closed-sandwich geometries (figs. 7(d) and (e)). At the present time, however, suitable analytical methods for treating the heat-transfer and meteoroid-protection characteristics of concepts other than the central fin geometry with simple armor protection are not available.

In order to illustrate the effects of radiator geometry on radiator area and weight, sample calculations were made for a Brayton cycle producing 100 kilowatts of electricity. Neon was the working fluid and the turbine inlet temperature was 2200° R. A flat plate radiator with centrally finned tubes and simple armor protection was assumed. Beryllium was used as the material for both the fins and tubes. Radiator weight, including headers, for this 100 kilowatt system is shown in figure 8 as a function of radiator panel area (product of radiator length and width) for several tube diameters. As panel area increases, radiator weight decreases to a minimum and then increases. Increasing panel area corresponds to increasing the distance between tubes. Such an increase in tube-to-tube distance has opposing effects on the radiator; on one hand, fin effectiveness decreases and the radiator becomes larger, while on the other hand, there is a decrease in tube outside area with a resultant decrease in meteoroid protection weight. The minimum weight occurs at the point where the reduction in armor weight no longer offsets the weight increase due to the decreased fin effectiveness. An unfinned radiator for the system under consideration would require a panel area of about 1230 square feet and would weigh about 6000 pounds. An optimum finned-tube configuration requires about 1350 square feet of panel area but weighs only 1350 pounds. It is therefore seen that there is a trade-

off between weight and area that depends on the selected radiator geometry. Figure 8 also shows the effect of tube size on radiator weight. As tube diameter decreases, minimum radiator weight decreases to a minimum and then increases. For the case shown in figure 8, the optimum tube diameter is about 0.375 inch. The decrease in weight with decreasing diameter is caused primarily by the armor weight being less for smaller tubes. As the tubes get smaller, however, this effect becomes less pronounced, and increasing header weight along with less favorable heat-transfer pressure-drop characteristics eventually cause an increase in total weight.

Armor material. - The choice of armor material has a significant effect on radiator weight. Armor thickness and weight depend upon both the density and modulus of elasticity of the armor material (ref. 9). For several armor materials of interest, relative thicknesses and weights for equivalent protection are tabulated below.

ARMOR MATERIAL COMPARISON

Armor material	Relative thickness	Relative weight
Beryllium	1.00	1.00
Aluminum	1.53	2.30
Stainless steel	.86	3.93
Molybdenum	.80	4.07

The tabulated values refer to flat plates; for tubes, these ratios will vary somewhat. Beryllium appears to have a considerable weight advantage as a meteoroid armor material. For the previously mentioned design requirements, aluminum and stainless-steel radiators would weigh about 3000 and 7800 pounds, respectively, as compared to 1350 pounds for the beryllium

radiator.

Internal flow characteristics. - Another important consideration as far as radiator area is concerned is the heat-transfer coefficient of the fluid in the radiator. If the heat-transfer coefficient is low, a considerable temperature drop, possibly in excess of 100° R, occurs between the fluid and the tube wall. This can occur primarily in low power output systems where the gas pressure must be fairly low in order to achieve reasonable turbomachinery geometries. Such a temperature drop is detrimental to the radiator, as can be seen from figure 9, where prime radiator area is plotted against a fluid heat-transfer coefficient relative to prime radiator area. This heat-transfer coefficient relative to prime radiator area is equal to the heat-transfer coefficient relative to the internal heat-transfer area times the ratio of internal heat-transfer area to prime radiator area. As seen from figure 9, radiator area changes very little for heat-transfer coefficients above 25 Btu/(hr)(sq ft prime radiator area)(OR); however, as heat-transfer coefficient decreases from 25 to 10, radiator area increases about 20 percent, and as heat-transfer coefficient decreases below 10, radiator area increases very rapidly. It is, therefore, desirable for the radiator fluid heat-transfer coefficient to be at least above 10 and preferably above 25. Since the internal heat-transfer coefficients associated with the gases of interest are relatively low, and the ratio of internal heat-transfer area to radiating area for a meteoroid-protected tube and fin radiator may easily be in the range 0.10 to 0.25, the heat-transfer coefficient relative to prime radiator area can, in many cases, drop below 10. For such cases, there are several things that can be done to remedy the situation. Internal fins

can be placed in the radiator in order to greatly increase the ratio of internal to radiating areas and, thereby, increase the heat-transfer rate between the gas and the wall. Another alternative is the use of a liquid cooling loop, such as that shown in figure 3, since the heat-transfer coefficients associated with liquids are usually much higher than those associated with gases.

Liquid radiator. - A liquid radiator, as indicated previously, offers a potential weight savings over a gas radiator. Panel area, however, will be larger for the liquid radiator because of the lower temperature and larger tube-to-tube distance for a minimum weight configuration. The weight savings potential of the liquid radiator can be attributed to the following factors: (1) smaller tube and header sizes due to the much greater density of the liquid, (2) larger allowable pressure drops because of the very small amount of power required to pump liquids, and (3) the larger heat-transfer coefficients of liquids. An additional potential advantage is that of increased mission reliability achieved through the use of several cooling loops in parallel. The disadvantages associated with a liquid radiator are the added complexity of a cooling loop, the additional weight of a gas cooler and a pump, and the larger radiator area. The choice of gas cooler effectiveness and liquid flow rate must be based on a minimization of the total weight of gas cooler and radiator. One liquid radiator, not necessarily the optimum one, for the previously mentioned 100 kilowatt system was found to require 2330 square feet and weigh 730 pounds as compared to 1950 square feet and 1350 pounds for the gas radiator. The gas cooler for this case would weigh about 250 pounds.

Many areas must be explored and problems solved before large efficient space radiators become a reality. Prominent among these areas which need clarification and/or development are (1) the meteoroid population density, (2) the meteoroid penetration mechanism, (3) the fabrication of beryllium into radiators, (4) surface coatings with favorable absorptivity-emissivity properties, (5) techniques for the analysis of complex internal and external finned-tube geometries, and (6) segmentation techniques.

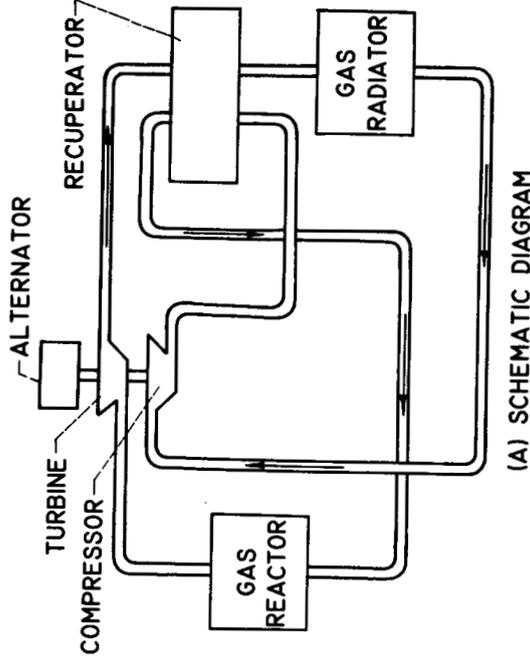
CONCLUDING REMARKS

Several proposed configurations for Brayton cycle space power systems have been described in this paper. The heat-transfer components (reactor, heat exchangers, and radiator) constitute an important part of such systems, and the performance of these components significantly affects such important system characteristics as cycle efficiency and radiator area. The achievement of good system performance depends to a large extent upon the ability of the heat-transfer components to perform with high heat-transfer and low pressure-drop characteristics. In addition, a high reactor operating temperature, preferably in excess of 2000° R, is desired in order to reduce the large radiator size.

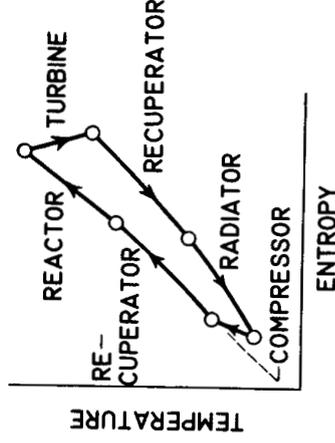
The basic technology for the Brayton cycle reactor and heat exchangers is in existence. However, development efforts are required in order to apply this technology at the high temperatures desired for Brayton cycle space power systems. Both research and development efforts are required to firmly establish the design criteria for large radiators for not only a Brayton cycle system but for all space power systems.

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(A) SCHEMATIC DIAGRAM



(B) THERMODYNAMIC DIAGRAM

Figure 1. - Brayton power cycle - one-loop system.

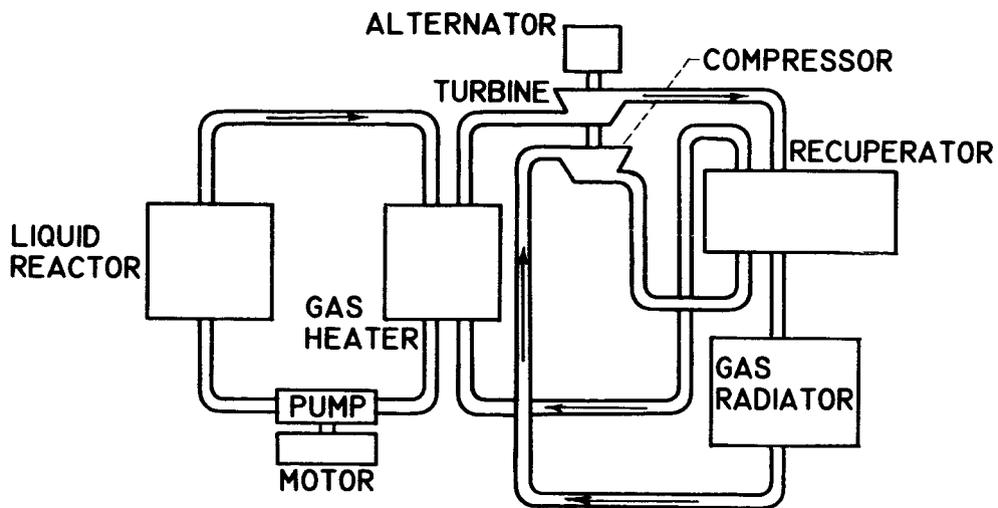


Figure 2. - Brayton power cycle - two-loop system.

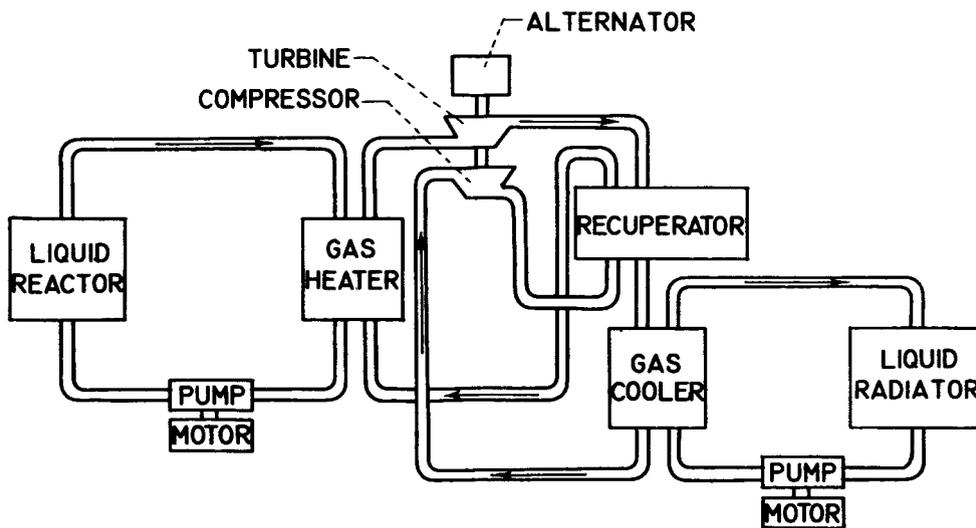


Figure 3. - Brayton power cycle - three-loop system.

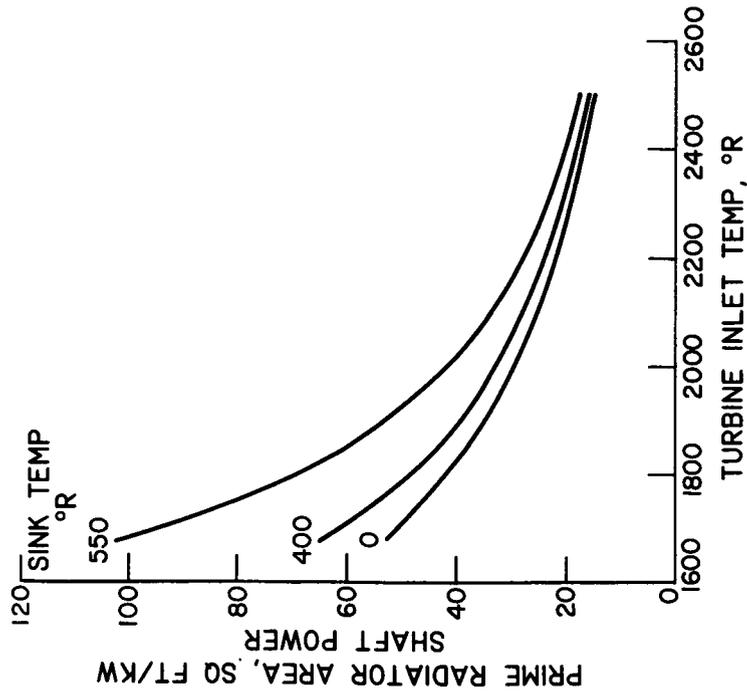


Figure 4. - Effect of turbine inlet and sink temperatures on prime radiator area for a typical system.

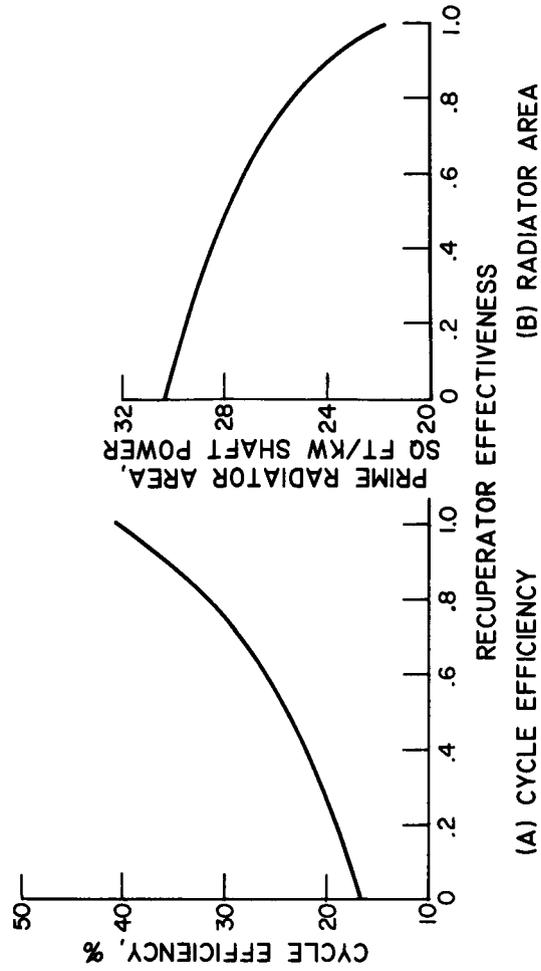


Figure 5. - Effect of recuperator effectiveness on cycle efficiency and prime radiator area for a typical system.

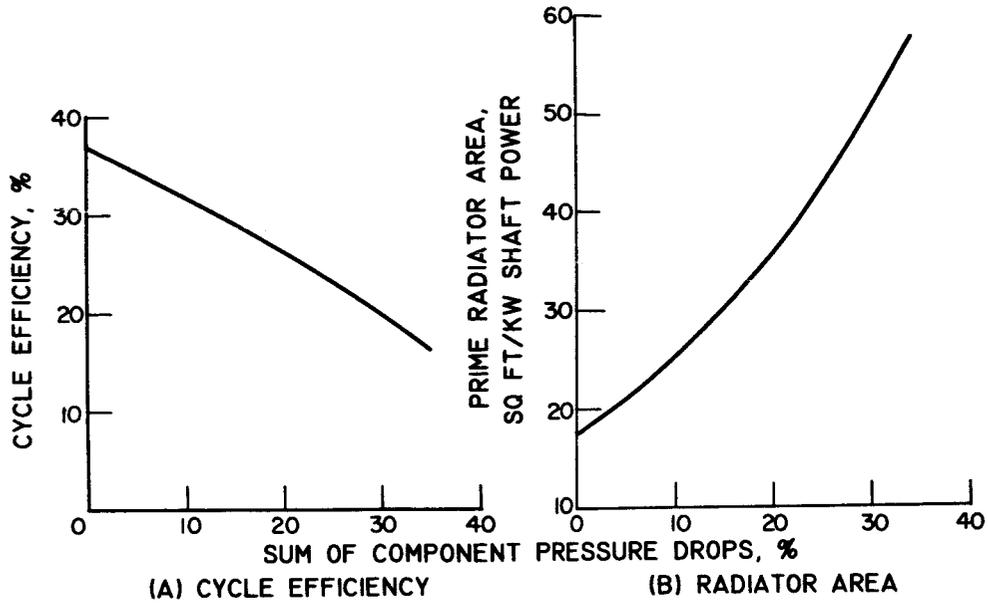
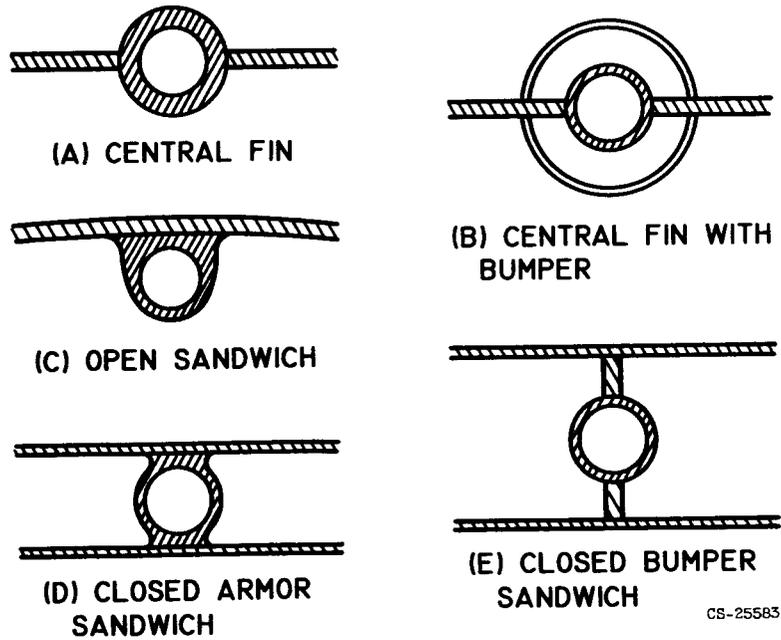


Figure 6. - Effect of component pressure drop on cycle efficiency and prime radiator area for a typical system.



CS-25583

Figure 7. - Finned tube geometries.

SYSTEM ELECTRICAL OUTPUT: 100 KW
 TURBINE INLET TEMP: 2200° R
 FLUID: NEON
 MATERIAL: BERYLLIUM

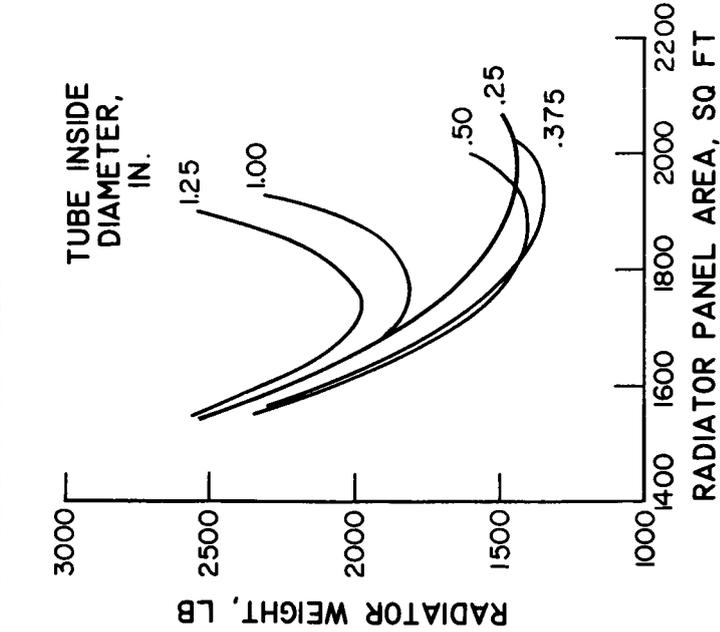


Figure 8. - Effect of radiator geometry on radiator weight.

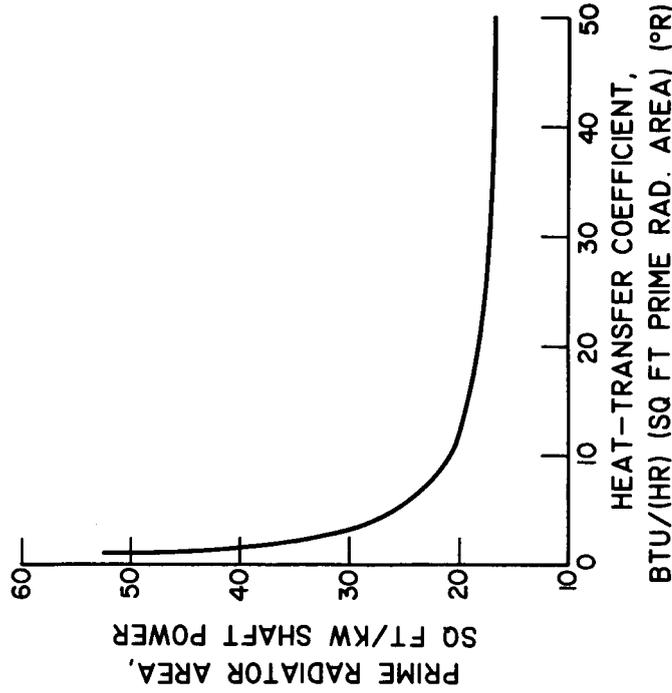


Figure 9. - Effect of fluid heat transfer coefficient on prime radiator area for a typical system.